

Experimental investigation on heat loss of semi-spherical cavity receiver



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ABSTRACT

In this paper, experiments were performed to investigate the heat loss of semi-spherical cavity receiver applied for solar dish collector. Experiments were conducted for fluid inlet temperatures from 75 °C to 150 °C, receiver inclination angles of 0° (cavity aperture facing sideways), 15°, 30°, 45°, 60° and 90° (cavity aperture facing down), and aperture size of 0.15 m, 0.2 m and 0.25 m. Total, conductive, convective and radiative heat loss were studied in low-temperature situations (75–150 °C) and extended to high-temperature situations (150–300 °C). Experimental correlations of Nusselt number as function of Grashof number were developed for different operating temperatures, inclinations and aperture sizes. Compared to numerical results of cavity receiver, the convective heat loss is higher in present work and with the reduction of inclination, the deviation is more obvious.

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1. Introduction

Solar thermal energy technology converts solar energy to thermal energy for power, heating, cooling and other forms of energy, and it has been regarded as one of the most promising technologies for large scale commercialization. Solar thermal energy technology can be classified based on collecting temperature. Solar dish system, with high concentration ratio and high operating temperature, has demonstrated the highest efficiency [1–3]. In solar dish system, collectors concentrate and reflects sunlight into cavity receivers, in which concentrated solar energy is transformed to thermal energy in working fluid like air, oil or molten salt [4–6]. Cavity receivers are preferred in parabolic dish solar thermal system due to advantages over other types of receivers [3]. The performance of cavity receiver is of great significance for energy conversion efficiency, and heat loss can subsequently effect the thermal performance of cavity receiver [3,7]. Therefore much previous research has been focused on the heat loss (including convective, conductive and radiative heat loss) of cavity receivers with different shapes and geometries from both theoretical and experimental methods.

From 1980s, different styles of cavity receivers were proposed and heat loss models were developed by analytical and numerical methods. Clausen developed an analytical model for calculation of convective heat loss for a cubical cavity receiver [8]. Le Quere et al. conducted numerical simulation on natural convection in a cubical cavity receiver, the authors found the convective heat loss is

strongly dependent on the cavity inclination [9]. Koenig and Marvin studied the convective heat loss of cylindrical cavity receiver and developed a correlation for Nusselt number as a function of Grashof number and Prandtl number [10]. The correlation was based on higher temperature. Stine and McDonald presented a Nusselt number correlation for a cylindrical shaped cavity receiver considering the effects of operating temperature, inclination of receiver and aperture size [11].

Paitoonsurikarn and Lovegrove conducted research on convective heat loss of cavity receiver with different geometries. They numerically investigated the nature convective heat loss considering the effect of factors like cavity geometry and inclination [12]. After that, Paitoonsurikarn and Lovegrove proposed a new correlation of convective heat loss based on simulation results of three different cavity receiver; this correlation was claimed more simple and accurate when estimating free convective loss [13]. Patila et al. presented a numerical study of heat loss from a non-evacuated receiver in order to optimize the design of the non-evacuated solar receiver for minimum heat loss by using CFD technique [14].

In order to validate the theoretical results and evaluate the difference between the numerical analysis and experimental data, experimental investigations on heat loss of cavity receivers were also conducted. Clausen compared the experimental data of convective heat loss based on a cubical cavity receiver to the estimation results developed by an analytical model [15]. Le Quere et al. conducted experiments on natural convection in a cubical cavity receiver, and an experimental correlation for Nusselt number at different inclinations was presented [16]. McDonald conducted an experimental investigation on cavity receiver; he proposed an analytical method for predicting the conductive and radiative heat loss, a

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Nomenclature

A_a	aperture area (m^2)	$Q_{\text{conv}@}\theta$	convective heat loss at angle θ (W)
A_{Da}	fitting coefficient in Eq. (6) (W)	$Q_{\text{plugged}@90^\circ}$	total heat loss at angle of 90° when aperture is plugged (W)
A_θ	fitting coefficient in Eq. (5) (W)	Q_{rad}	radiative heat loss (W)
B_{Da}	fitting coefficient in Eq. (6) (m^2/W)	$Q_{\text{rad}@D_a}$	radiative heat loss for aperture size of D_a (W)
B_θ	fitting coefficient in Eq. (5) (W/K)	Q_{total}	total heat loss (W)
C_p	specific heat of oil (W/kg K)	$Q_{\text{total}@90^\circ}$	total heat loss at angle of 90° (W)
C_θ	fitting coefficient in Eq. (7) (W)	$Q_{\text{total}@}\theta$	total heat loss at angle θ (W)
D	diameter of receiver (m)	T_a	ambient temperature ($^\circ\text{C}$)
D_a	aperture size (m)	T_i	inlet temperature of receiver ($^\circ\text{C}$)
D_θ	fitting coefficient in Eq. (7) (W/K)	T_m	mean temperature of receiver ($^\circ\text{C}$)
Gr_D	Grashof number based on diameter of receiver	T_o	outlet temperature of receiver ($^\circ\text{C}$)
h	heat transfer coefficient ($\text{W}/\text{m}^2 \text{K}$)	λ	thermal conductivity of air ($\text{W}/\text{m K}$)
m	mass flow rate of oil (kg/s)	θ	angle of receiver ($^\circ$)
Nu_D	Nusselt number based on diameter of receiver	σ	Stefan–Boltzmann constant ($\text{W}/\text{m}^2 \text{K}^4$)
Q_{cond}	conductive heat loss (W)		
Q_{conv}	convective heat loss (W)		

convective heat loss correlation was also developed based on experimental results [17]. Taumoeofolau conducted an experimental simulation on a cavity receiver by electrical heating and studied the convective heat loss under laboratory conditions [18]. Prakash et al. presented a numerical and experimental investigation of heat loss for cylindrical cavity receiver with a wind skirt [19]. In his research, correlations of Nusselt number in both low and high operating temperatures were developed based on experimental results and prediction results. Xie et al. proposed and tested a point focus solar collector using high concentration imaging PMMA Fresnel lens prototype to find the optimum cavity type [20].

In 2000, Kaushika and Reddy represented and compared thermal performance characteristics of semi-spherical cavity and modified cavity receiver applied for low cost solar paraboloidal dish system, and the modified cavity receiver was claimed to be with higher efficiency [21]. In this case, the modified cavity receiver has advantages over other types of cavity receivers because a cavity absorber with relatively large aperture would be required which, in turn, would involve large energy losses. In addition, from the literature review, despite a wide variety of cavity receivers with different types and geometries have been studied, the correlation of heat loss cannot be applied widely to accurately estimate heat loss of cavity receivers with different types. Taking Paitoonsurikarn's correlation [13] as an example, the proposed correlation can predict approximately 50% of the data within $\pm 20\%$ and 90% of the data within $\pm 50\%$, therefore some researchers continued the investigation in heat loss of semi-spherical cavity receiver.

Sendhil Kumar and Reddy applied a two-dimensional model to simulate the natural convection heat loss for modified cavity receiver applied for solar dish concentrator, and correlations of Nusselt number for cavity both “with insulation” and “without insulation” were proposed [7]. Afterwards, they numerically studied and compared the nature convective heat loss of cavity receiver, semi-cavity receiver and modified cavity receiver applied for solar dish collector, and the optimum aperture size ratio was found for minimum heat loss of receiver [22]. Reddy and Sendhil Kumar improved their study with a three-dimensional numerical model of modified cavity receiver [23]. The new model were more accurate in convective heat loss calculation compared to their previous two-dimensional model. After that, they added surface radiation heat transfer into former two-dimensional numerical model combined with laminar convective heat loss and surface radiation [24]. For semi-spherical cavity receiver, even though much research has been done by numerical simulation [7,22–24], to the authors' knowledge, there has been few previous experimental investigations. Yasuaki et al. experimentally studied the natural convection in a hemisphere heated from below to clarify the basic characteristics of natural convection in the hemi-sphere experimentally with the bottom surface heated and the semi-spherical surface cooled. Correlation between heat transfer rate and Tayleigh number was obtained [25]. Khubeiz et al. experimentally studied the laminar free-convection heat transfer from an isothermal semi-spherical cavity in unlimited space, the results of experimental procedure is compared with theoretical analysis and numerical

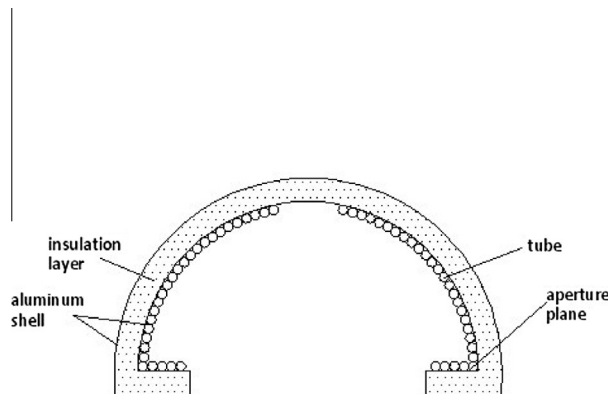


Fig. 1. Solar cavity receiver presented in this paper.

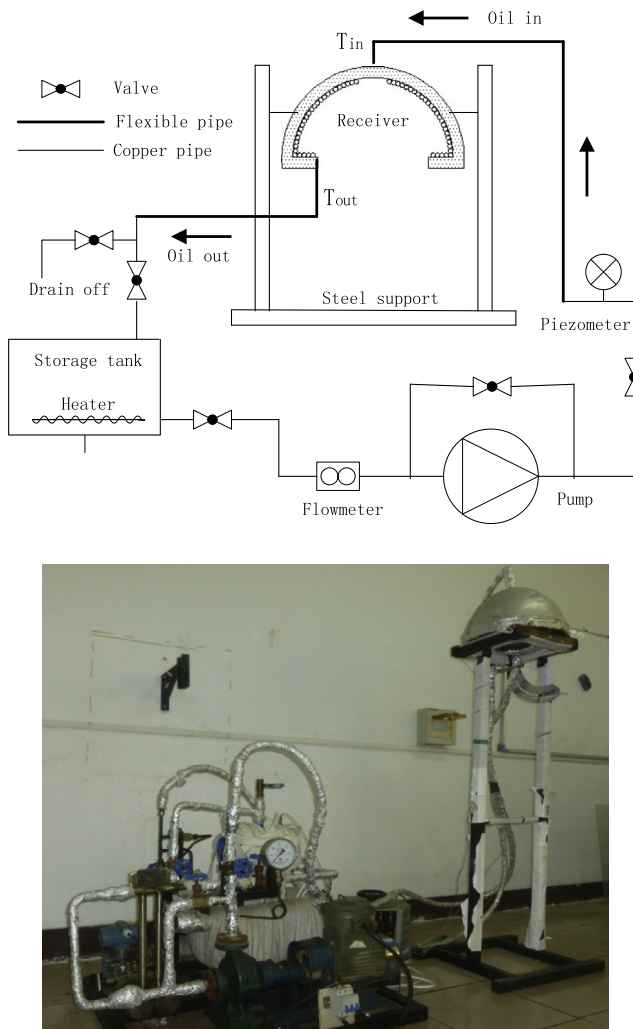


Fig. 2. Schematic and photograph of the experimental system.

simulation using FLUENT/UNS code [26]. It is necessary to experimentally develop the heat loss model of semi-spherical cavity receiver to validate the numerical results as well as to evaluate the difference between numerical results and experimental data. The present paper focuses on experimental investigation of heat loss for semi-spherical cavity receiver applied for solar dish system. An indoor experiment is set up to study the heat loss, including total, conductive, convective and radiative heat loss with the variation of factors like operating temperature, aperture size and inclination of cavity receiver.

2. Receiver in present study

The semi-spherical receiver used in current investigation is shown in Fig. 1. The copper tubes are wound spirally around the inner surface of semi-spherical curve and the bottom of the aperture plane, separately 23 and 5 turns. Cavity diameter of the receiver is 0.35 m and aperture diameter of the receiver is 0.25 m. The copper tube has a diameter of 0.01 m. The outer surface of the receiver is covered by mineral wool insulation with 25 mm thickness to reduce the heat loss. Another aluminum semi-spherical shell and aperture plate are provided to fix the thermal insulation layer.

Table 1
Total heat loss of the cavity receiver.

D_a (m)	90°				60°				45°				30°				15°				0°			
	T_i (°C)	T_o (°C)	Q_{total} (W)		T_i (°C)	T_o (°C)	Q_{total} (W)		T_i (°C)	T_o (°C)	Q_{total} (W)		T_i (°C)	T_o (°C)	Q_{total} (W)		T_i (°C)	T_o (°C)	Q_{total} (W)		T_i (°C)	T_o (°C)	Q_{total} (W)	
0.25	75.6	71.7	164		74.9	70.7	181		75.2	70.5	202		75.4	70.3	216		76.0	70.6	231		75.6	68.4	307	
	100.9	95.3	249		100.4	93.9	278		100.3	93.4	292		100.4	92.7	320		100.6	92.4	355		100.9	91.8	409	
	124.7	117.3	307		124.6	115.9	363		125.0	115.7	373		125.4	115.5	405		125.6	114.2	467		125.8	112.9	528	
	150.2	139.9	413		149.5	137.7	480		149.5	136.3	526		149.8	136.2	548		150.7	136.4	585		149.9	134.3	651	
0.2	75.8	71.7	164		75.0	71.1	168		75.3	70.7	193		75.9	70.7	204		75.7	69.9	246		75.4	68.7	285	
	100.3	94.7	248		100.0	93.9	262		100.1	93.4	287		100.3	93.4	292		100.1	92.4	333		100.2	91.6	371	
	125.3	118.1	298		124.9	117.2	323		125.0	116.6	353		125.0	115.8	380		124.9	114.3	447		125.2	113.7	482	
	150.2	141.2	377		149.3	139.6	401		149.6	138.9	431		149.6	138.6	451		149.9	136.2	549		149.9	135.3	595	
0.15	75.3	71.7	158		75.1	71.3	160		74.9	71.0	166		75.1	71.1	171		75.6	70.9	201		75.4	69.4	255	
	101.3	95.8	237		101.1	95.5	247		101.5	95.5	260		101.1	94.6	287		101.2	93.4	342		100.8	92.4	363	
	126.2	119.4	283		125.3	118.4	291		125.4	117.7	319		125.5	117.1	356		125.3	116.3	386		124.6	114.7	438	
	150.7	141.5	373		150.7	141.1	384		150.8	140.5	417		150.4	139.7	453		150.9	139.2	487		149.7	136.6	544	

3. Experimental investigation

3.1. Experimental system

The schematic and the photograph of the experimental set-up for the heat loss tests of the receiver are shown in Fig. 2. The experimental system consists of following main components: storage tank, differential pressure flow meter, oil pump, piezometer, cavity receiver. The oil tank with 6 L capacity has an electric heater (1.5 kW) inside serving as the heat source of oil. Temperature of oil in the storage tank is controlled by a thermostat, driving a solid relay connected to the electric heater. Differential pressure flow meter is used to measure the flow rate of oil up to 300 °C with measurement range of 0–500 L/h. A 0.75-kW oil pump is used for circulating the oil through the receiver tubes. Bypass pipe with a flow regulating valve is set to control the flow rate of oil out of the pump. To inspect the pressure of the system, a piezometer (ranging from 0 to 0.6 MPa) is installed after the pump. The cavity receiver is supported by a steel stand so that it can be inclined at random angles from 0° (cavity aperture facing sideways) to 90° (cavity aperture facing down).

In the heat loss tests, SYLTHERM 800 heat transfer fluid is used as working fluid within the circulating system. SYLTHERM 800 heat transfer fluid is a highly stable, long-lasting, low-viscosity silicone fluid designed for high temperature liquid phase operation [27]. Temperatures of fluid in the tube (inlet and outlet of cavity receiver) and in storage tank are measured by T-type thermocouples. Data are logged onto a computer via Agilent 34980A data acquisition instrument.

All the measuring instruments used in the experiments are calibrated. The T-style thermocouples have an uncertainty of $\pm 0.5^\circ\text{C}$ for measurements between 50 °C and 200 °C. The differential pressure flow meter has an uncertainty of $\pm 0.5\%$ for 100 L/h measurement.

3.2. Experimental procedure

This paper investigates three factors that influence the thermal performance of the receiver: inclination of the receiver, inlet temperature of oil, size of the aperture. Heat loss were tested at receiver inclination of 0°, 15°, 30°, 45°, 60° and 90° with different inlet temperatures from 75 °C to 150 °C, every 25 °C. Aperture size is another essential factor that effects heat loss of the receiver, the aperture size tested were 0.15 m, 0.2 m and 0.25 m respectively. Annulus were used to change the size of aperture [7]. The annulus is fabricated by hard low-conductive support wrapped with insulation material. The heat transfer fluid circulated into the cavity receiver from the top entrance and flowed out of the receiver from the exit near the aperture, which guarantees that the temperatures at the top was higher than temperatures near the aperture similar to the situation in the on-flux operation outdoors. The flow rate of the oil was maintained steady at 100 L/h. Generally, it would take 2 h to maintain the system steady when values of factors changed. The ambient temperature is measured at a location not affected by the receiver temperatures.

4. Heat loss model

Heat loss of cavity receiver consists of total, conductive, radiative and convective heat loss. The total heat loss from the cavity receiver can be estimated as follows:

$$Q_{\text{total}} = mC_p(T_i - T_o) \quad (1)$$

Here value of m , T_i and T_o can be obtained from the experiments, value of C_p can refer to the property data of SYLTHERM 800 heat

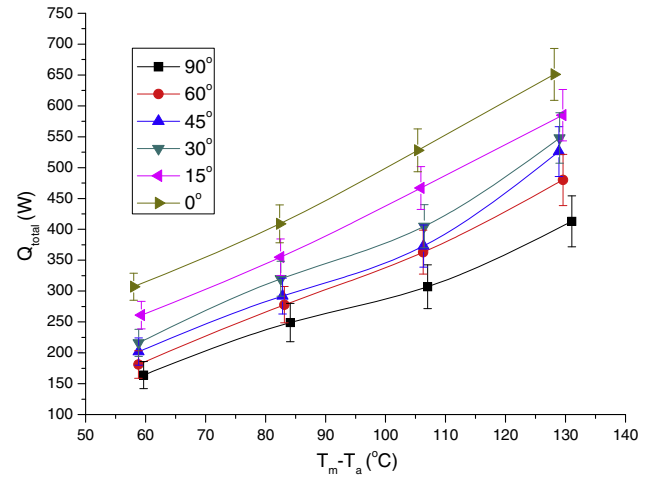


Fig. 3. Variation of total heat loss with temperature difference for $D_a = 0.25$ m.

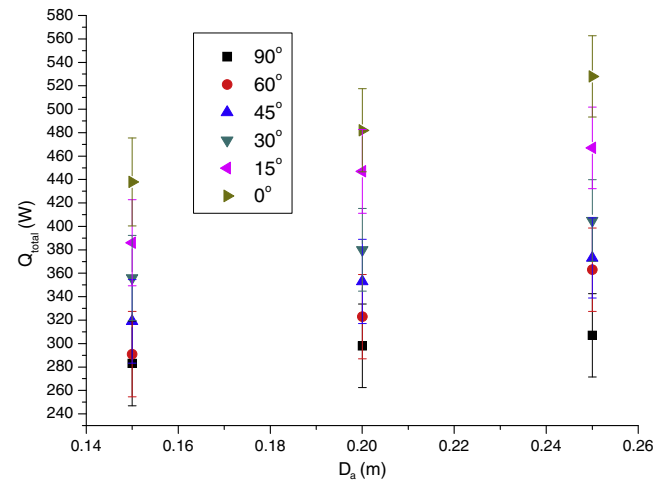


Fig. 4. Variation of total heat loss with aperture size for $T_i = 125^\circ\text{C}$.

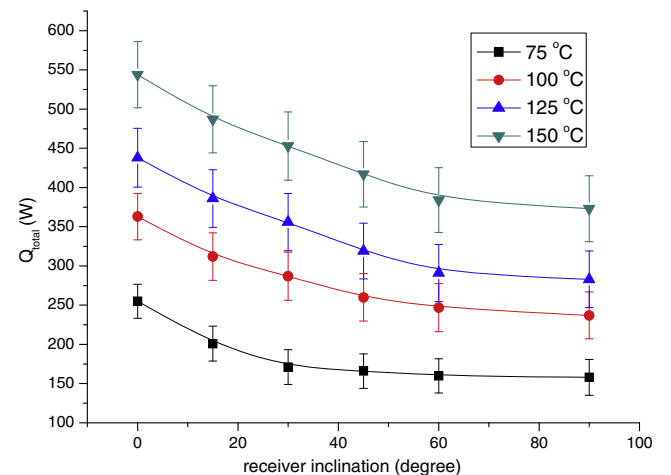


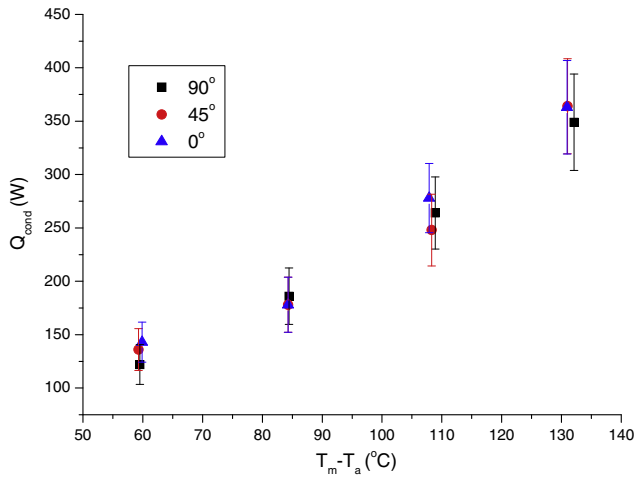
Fig. 5. Variation of total heat loss with receiver inclination for $D_a = 0.15$ m.

transfer fluid. The conductive heat loss of the receiver is the heat loss through the insulation wrapping the copper tubes. Conductive heat loss is relatively convenient for measurement by normal

Table 2

Conductive heat loss of the cavity receiver.

D_a (m)	90°			45°			0°		
	T_i (°C)	T_o (°C)	Q_{cond} (W)	T_i (°C)	T_o (°C)	Q_{cond} (W)	T_i (°C)	T_o (°C)	Q_{cond} (W)
Plugged	75.2	71.8	122	75.1	71.5	136	75.9	71.9	143
	100.9	96.0	186	100.7	95.9	178	100.7	95.9	178
	126.3	119.5	264	125.5	119.1	248	125.6	118.2	278
	150.1	142.1	349	149.2	140.8	364	149.2	140.7	363

**Fig. 6.** Variation of conductive heat loss with temperature difference ($T_m - T_a$) when aperture plugged.**Table 3**Values of A_θ and B_θ .

Inclination	90°		45°		0°	
	A_θ	B_θ	A_θ	B_θ	A_θ	B_θ
	-70.9	3.1	-68.8	3.1	-66.2	3.1

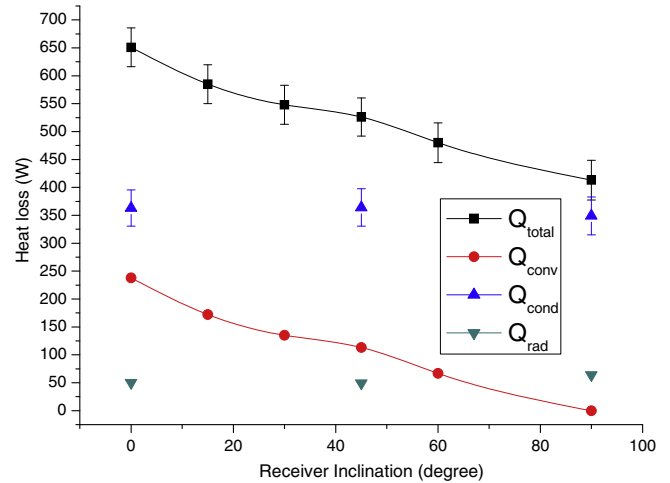
Table 4Values of A_{Da} and B_{Da} .

D_a (m)	0.25		0.2		0.15	
	A_{Da}	B_{Da}	A_{Da}	B_{Da}	A_{Da}	B_{Da}
	37.6	0.030	37.4	0.024	38.9	0.010

experiments similar to experimental investigation of total heat loss. Conductive heat loss can be obtained by inverting an insulated plug in the aperture; this method was used in previous papers [17]. The radiative heat loss in this study is the radiation energy from the inner surface of the cavity receiver to environment via the aperture. Radiative heat loss can be estimated by analytical method related to geometric configuration and those calculation equations always involve temperature of inner surface of cavity receiver and emissivity of inner surface material. However, the temperature field distribution is not uniform and emissivity of material is hard to obtain after material process, thus it is not accurate to estimate radiative heat loss. Based on the previous methods, this paper chooses the method applied for $Q_{conv@90^\circ} = 0$ condition, the heat loss can be calculated as follows:

$$Q_{cond} = Q_{plugged@90^\circ} \quad (2)$$

$$Q_{rad} = Q_{total@90^\circ} - Q_{cond} \quad (3)$$

**Fig. 7.** Variation of heat loss with receiver inclination at $T_i = 150^\circ\text{C}$ and $D_a = 0.25$ m.

$$Q_{conv@90^\circ} = Q_{total@90^\circ} - Q_{cond} - Q_{rad} \quad (4)$$

The method adopted in this paper to estimate the heat loss of cavity receiver is based on the assumption of $Q_{conv@90^\circ} = 0$. This assumption can be supported by the results estimated by previous investigation. The convective heat loss of cavity receiver at angle of 90° is zero [8,15,11,17]; in $Q_{conv@90^\circ} \neq 0$ condition [22,13], convective heat loss is relatively small which can be neglected when operating temperature is under 400°C .

5. Results and discussion

In this part, the total, conductive, radiative and convective heat loss of the cavity receiver gained from the indoor experiments are discussed. Nusselt number correlations are proposed for the convective loss and compared with those presented in the previous papers.

5.1. Total heat loss

Table 1 shows the total heat loss result of cavity receiver obtained from the experiments at different aperture sizes (0.15 m, 0.2 m, 0.25 m), different receiver inclinations (90° , 60° , 45° , 30° , 15° , 0°) and different inlet oil temperatures (75°C , 100°C , 125°C , 150°C).

Fig. 3 shows the variation of total heat loss of cavity receiver with temperature difference ($T_m - T_a$) for aperture size of 0.25 m, T_m is the average of inlet and outlet temperature. T_a represents ambient temperature, which ranged from 13.5 to 14.5°C during experiment period. From Fig. 3, it is obvious that total heat loss of receiver increases along with increment of temperature difference at each receiver inclination. At certain temperature difference, increment rate of total heat loss from 30° to 0° is much greater than that from 90° to 60° and that from 60° to 30° . The

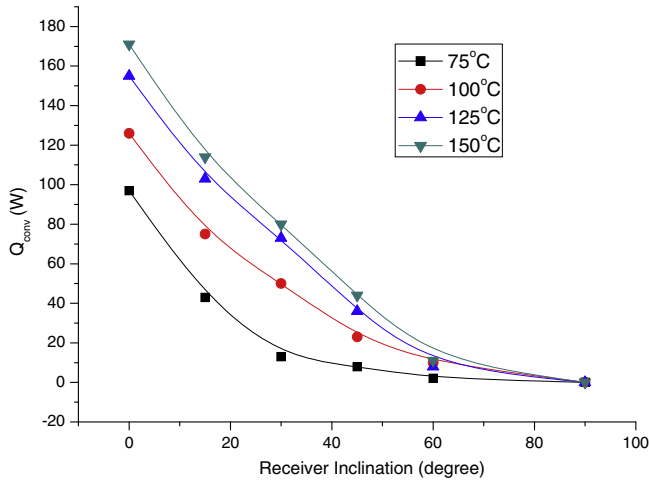


Fig. 8. Variation of convective heat loss with receiver inclination for $D_a = 0.15$ m.

similar variation tendency can be concluded by the data of aperture size of 0.2 m and 0.15 m.

Variation of total heat loss of cavity receiver with aperture size for T_i of 125 °C is showed in Fig. 4. It illustrates that the total heat loss of receiver increases along with increment of aperture size at each receiver angle. Similar to the result of Fig. 3, increment rate of total heat loss from 30° to 0° is much greater than that from 90° to 60° and that from 60° to 30° at each aperture size. The similar variation tendency can be concluded by the data of inlet oil temperature of 75 °C, 100 °C and 150 °C.

Fig. 5 displays the variation of total heat loss with receiver inclination for aperture size of 0.15 m, it shows that with the growth of receiver inclination, the total heat loss decreases at each inlet oil temperature, and the variation rate gradually diminished, reaching the minimum value at receiver inclination of 90°. In addition, comparing the four curves, with the reduction of receiver angle, the slopes of four curves tends to be approximately similar, which is beneficial to give a fairly accurate forecast for heat loss in higher operation temperatures cases. Above analysis conclusions can be also obtained by the data of aperture size of 0.2 m and 0.25 m.

5.2. Conductive heat loss

Table 2 shows the conductive heat loss of the cavity receiver at different inlet oil temperatures and different receiver inclinations

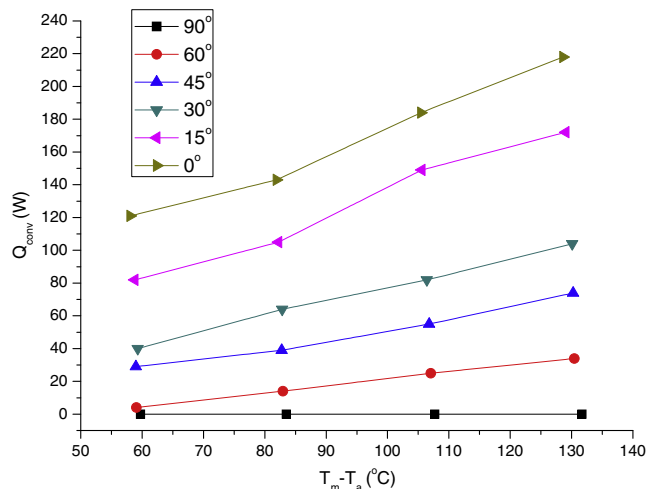


Fig. 9. Variation of convective heat loss with temperature difference for $D_a = 0.2$ m.

Table 5

Values of C_θ and D_θ .

D_a (m)	0.25		0.2		0.15	
	C_θ	D_θ	C_θ	D_θ	C_θ	D_θ
90°	0	0	0	0	0	0
60°	-28.7	0.75	-21.0	0.42	-2.3	0.10
45°	-34.5	1.06	-10.9	0.63	-20.3	0.50
30°	-21.8	1.17	-11.8	0.89	-35.5	0.94
15°	21.4	1.19	1.0	1.14	-12.1	1.01
0°	52.1	1.48	35.0	1.41	37.0	1.07

of 90°, 45° and 0°. It shows that the conductive heat loss of cavity receiver increases with the growth of inlet oil temperature at each receiver angle, value of conductive heat loss at a certain inlet oil temperature at each inclination varies but keeps relatively constant.

Fig. 6 shows the variation of conductive heat loss of cavity receiver with temperature difference ($T_m - T_a$) when aperture plugged. From Fig. 6, it is obvious that conductive heat loss of receiver increases along with increment of temperature difference at each receiver inclination. In addition, Fig. 6 also shows that the values of conductive heat loss follow a linear trend with temperature difference ($T_m - T_a$) and the similar relationship can also be found in previous receiver model [22], which can be applied to predict the conductive heat loss of the receiver at higher fluid temperature.

A linear relation has been fitted to the data and is of the form as follow, each receiver inclination has a value of A_θ and B_θ as shown in Table 3 the slope value of linear relation at different inclinations is 3.1, and the difference of intercept value of linear relation at different inclinations is small, therefore conductive heat loss keeps almost the same with variation of inclination and can be calculated by following equation:

$$Q_{cond@ \theta} = A_\theta + B_\theta(T_m - T_a) \quad (5)$$

5.3. Radiative heat loss

Radiative heat loss has been studied by both analytical and experimental methods in previous papers, and the radiative heat loss can be presented as function of T_m^4 [17,22] or $(T_m^4 - T_a^4)$ [8,15,9,16,10]. In this study, the equation of radiative heat loss as function of $(T_m^4 - T_a^4)$ has been fitted as follow and values of A_{Da} and B_{Da} for each receiver aperture size are shown in Table 4.

$$Q_{rad@Da} = A_{Da} + B_{Da}\sigma(T_m^4 - T_a^4) \quad (6)$$

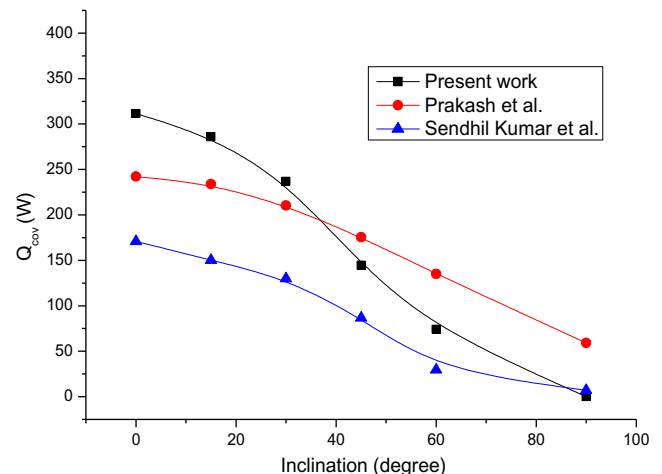


Fig. 10. Comparison of convective heat loss at $D_a = 0.2$ m, $T_m = 300$ °C.

5.4. Convective heat loss

From the above analysis, total heat loss, convective heat loss, conductive heat loss and radiative heat loss can be estimated respectively. Fig. 7 displays four kinds of heat loss of cavity receiver with receiver inclination at $T_i = 150^\circ\text{C}$ and $D_a = 0.25$ m. Variation of convective heat loss with receiver inclination for $D_a = 0.15$ m shows in Fig. 8. It shows that the convective heat loss of receiver decreases along with increment of inclination at each temperature difference, increment of total heat loss from 30° to 0° is much obvious than that from 90° to 60° and that from 60° to 30° .

Fig. 9 shows the variation of convective heat loss of cavity receiver with temperature difference ($T_m - T_a$) for aperture size of 0.2 m. From Fig. 9, it is obvious that convective heat loss of receiver increases along with increment of temperature difference at each receiver inclination. At certain temperature difference, increment rate of total heat loss from 30° to 0° is much greater than that from 90° to 60° and that from 60° to 30° . The similar variation tendency can be also concluded by the data of aperture size of 0.25 m and 0.15 m. In addition, Fig. 9 also shows that the values of convective heat loss follow a linear trend with temperature difference ($T_m - T_a$), which can be applied to predict the convective heat loss of the receiver at high fluid temperature.

A linear relation has been fitted to the data and is of the form as follow, and values of C_θ and D_θ at each receiver inclination are shown in Table 5. Such similar relationship has been found in previous literature [11,19].

$$Q_{conv\theta} = C_\theta + D_\theta(T_m - T_a) \quad (7)$$

5.5. Correlation developed

5.5.1. Correlation of Nu_D at low fluid temperature

Based on the convective heat loss of cavity receiver obtained from the experiments at different aperture sizes (0.15 m, 0.2 m, 0.25 m), different receiver inclinations (90° , 60° , 45° , 30° , 15° , 0°) and different inlet oil temperatures (75°C , 100°C , 125°C , 150°C), Nu_D can be calculated by Eqs. (8) and (9). Here h is heat transfer coefficient based on the aperture area, λ is thermal conductivity of air, Q_{conv} is convective heat loss, T_m and T_a represent the average of inlet and outlet temperature and ambient temperature, A_a is area of aperture.

$$Nu_D = \frac{hD}{\lambda} \quad (8)$$

$$h = \frac{Q_{conv}}{(T_m - T_a)A_a} \quad (9)$$

The correlation of Nusselt number is function of Grashof number (based on diameter of the receiver), inclination of receiver, temperature ratio and diameter ratio, therefore correlation of Nu_D at low fluid temperature can be developed as follow:

$$Nu_D = 0.001(Gr_D)^{0.398}(1 + \cos \theta)^{7.673} \left(\frac{T_m}{T_a}\right)^{-0.074} \left(\frac{D_a}{D}\right)^{-0.407} \quad (10)$$

where Gr_D is Grashof number based on diameter of cavity receiver, which varies from 1.9×10^8 to 2.8×10^8 , θ is inclination of cavity receiver, T_m and T_a represent the average of inlet and outlet temperature and ambient temperature, value of T_m/T_a is between 1.2 and 1.5, D_a and D are diameter of aperture and cavity receiver, and value of D_a/D ranges from 0.43 to 0.72. The Adjusted R -Square of the correlation is 0.997 with approximately 90% of the data within $\pm 20\%$ and 100% of the data within $\pm 30\%$.

5.5.2. Correlation of Nu_D at high fluid temperature

Correlation of Nu_D at low fluid temperature (Eq. (10)) can be applied to predict convective heat loss of cavity receiver when T_m is lower than 150°C , however, according to actual engineering experience, operating temperature of working fluid in cavity receiver can reach 300°C or even higher, thus developing correlation of Nu_D at high fluid temperature is necessary. Based on Eq. (7) and coefficient from Table 5, convective heat loss of receiver at different inclinations with different aperture sizes can be estimated, similar to the method used in correlation development at lower fluid temperature, the correlation of Nu_D can be obtained. Eq. (11) represents developed correlation of Nu_D when the value of T_m/T_a is between 1.5 and 2.0.

$$Nu_D = 0.540(Gr_D)^{0.142}(1 + \cos \theta)^{5.699} \left(\frac{T_m}{T_a}\right)^{-0.477} \left(\frac{D_a}{D}\right)^{-0.556} \quad (11)$$

5.5.3. Comparison with previous study

As it shows in Fig. 10, convective heat loss results predicted by present model has been compared with models of Prakash et al. [19] and modified cavity receiver [22] with variation of inclination when T_m is 300°C and D_a is 0.2 m. Prakash's model was developed from experimental results and Kumar's numerical model was based on modified cavity receiver, which is the same type receiver studied in present work. As shown in Fig. 10, it is evident that the deviation exists between different models. Compared to numerical results of modified cavity receiver estimated from Kumar and Reddy's model [22], the convective heat loss is higher at different inclinations in present work, and with the reduction of inclination, the difference is more obvious.

6. Conclusion

In this paper, heat loss, including total loss, conductive loss, radiative loss and convective loss of semi-spherical solar cavity receiver is studied via indoor experiments considering factors as inlet temperature, inclination and aperture size. The following conclusions can be drawn from this study:

- (1) Heat loss (including total, conductive, radiative and convective heat loss) has been experimentally investigated in low-temperature situations (75 – 150°C) and extended to high-temperature situations (150 – 300°C).
- (2) The correlation for Nusselt number (Nu_D) for convective heat loss at low fluid temperature (inlet temperature lower than 150°C) is developed with Adjusted R -Square of the correlation 0.997.
- (3) Extension of convective heat loss is developed at high fluid temperature ($150^\circ\text{C} < T_m < 300^\circ\text{C}$). Correlation of Nusselt number (Nu_D) of convective heat loss is developed at high fluid temperature and compared with correlations of convective loss in previous studies. Compared to numerical results of modified cavity receiver, the convective heat loss is higher in present work and with the reduction of inclination, the deviation is more obvious.

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